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Flexural performance of FRP-strengthened concrete beams: a review

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Abstract

The flexural performance of FRP-strengthened beams has become a critical focus in concrete structural engineering, particularly for enhancing strength, ductility, and durability. This paper provides a critical review of recent advancements in the use of FRP materials for flexural strengthening of concrete beams, emphasizing experimental findings, theoretical models, and practical applications. Key parameters affecting flexural performance—such as FRP type (carbon, glass, aramid), bonding techniques, and failure mechanisms—are thoroughly examined. While FRP materials offer advantages like a high modulus-to-weight ratio and corrosion resistance, challenges such as delamination, environmental durability, and cost remain significant. Additionally, emerging trends in reinforced or hybrid FRP systems are discussed. This review aims to offer researchers, engineers, and professionals comprehensive insights to develop effective and innovative solutions for concrete beam strengthening.

Keywords: *Failure, Reinforced concrete beams, Flexural behaviour, Fibre reinforced polymer.*

1. Introduction

Deterioration of concrete, loss of early strength, loss of workability, and eventual loss of strength of reinforced concrete components are frequently consequences of steel reinforcement corrosion. The problem is most acute in the marine, mining, and industrial environments and structures continually exposed to de-icing salts [1]. A 50-year design life is normally assumed in RC structures [2].

The two common manifestations of corrosion in RC structures are general or uniform corrosion and localized corrosion or pitting corrosion [3-5]. A prerequisite for pitting corrosion is the penetration of chloride ions into the concrete and concentration at a certain depth of the reinforcement. For all this, an additional prerequisite is the availability of moisture and oxygen at the steel surface [6-8]. Two primary sources of chloride ingress into concrete are by mixing water, aggregates, or admixtures contaminated with chlorides; and from outside sources, such as seawater or other sources of chlorides.

General corrosion in reinforced concrete, unlike localized corrosion, typically results from the carbonation process. Carbonation occurs when atmospheric carbon dioxide infiltrates the concrete and reacts with calcium hydroxide, forming calcium carbonate [9]. This reaction lowers the concrete's pH from its usual range of 13 to 13.8 to more neutral levels, sometimes reaching as low as 8.5. The reduction in pH weakens the passive oxide film that protects the steel reinforcement from corrosion [10].

Once carbonation reaches the steel surface, the breakdown of this protective layer accelerates corrosion, provided that sufficient oxygen and moisture are present. Otieno et al. [1] noted that chloride-induced corrosion is generally more prevalent than carbonation-induced corrosion.

Steel reinforcement often begins as a local attack, but in RC, it usually turns into a rapid macro-cell corrosion, which severely damages the surrounding concrete and hence the structure. The rusting of steel inside concrete probably causes concrete cover scaling because the rust of steels increases nearly four times the volume of steel; this phenomenon leads to internal tensile forces, consequently cracking, delaminating, and spalling concrete [11]. The cross-sectional area of the steel and the bond between steel and concrete reduce even further the structure's load-bearing capacity [12, 13], as shown in Figure 1.

The rate at which corrosion occurs is a critical parameter upon which to evaluate the remaining service life of a corroding RC structure [15]. Even though proper concrete cover and high alkalinity in the concrete solution present a delay in the start of the corrosion, it is an inevitable process over time [15]. Other contributory factors are the gradual concrete cover

deterioration resulting from pore continuity within the concrete matrix as well as the bad material quality and workmanship [16]. These challenges are very important for marine exposure since proper durable quality reinforcement material is needed for the long-lasting concrete structure.
In the past few years, there is increasing interest in the use of fiber-reinforced polymer (FRP) bars as a structural material for the reinforcement of concrete members both in new construction and structural rehabilitation from inside as well as outside, exposed faces of concrete structures [17-21]. FRP reinforcement provides many advantages over traditional materials, including steel, due to better physical, mechanical, and chemical properties. The FRP composites presented good corrosion resistance, were non-magnetic, had high strength-to-weight ratio properties as well as very good chemical durability [22-27]. These characteristics added to the extensive research that has gone into the study of the performance, durability as well as the field application of concrete beams reinforced with FRP bars [21, 28-32].
The aim objective of this paper is to analyse the effect of FRP materials on the bending capacity and structural behaviour of concrete beams. In the study, the primary concern is normally directed towards the effect of FRP on the load-carrying capacity, stiffness, and crack resistance. In addition, the study will determine the strengthening techniques, modes of failure as well as the parameters that might affect flexural performance among them FRP type, bonding methods, and reinforcement configurations.

Fig. 1: Corrosion of steel bars in RC structures [14].

2. Engineering properties of FRP

Fiber-reinforced polymer (FRP) composite comprises a matrix of polymers where the fibers are also called resin. Besides holding the fibers in place, this function secures the load as well as the protection of the fibers against environmental damage. Generally, fibers in most cases contribute the better part of ultimate strength and elastic modulus in a composite because their tensile strength is significantly greater than that of the matrix. Common types of fibers used in FRP composites are basalt, carbon, glass, and aramid [33], [34].
Since its inception into the construction industry in the 1960s FRP has been extensively studied as one of the possible alternatives to steel reinforcement [35]. FRP is highly regarded for its superior attributes such as low weight, high tensile strength, resistance against corrosion, and non-magnetic nature. Drawbacks common to FRP bars include bond strength being less than that available with steel bars, vulnerability to rupture failure, and the reduced elastic modulus as compared to steel [35]. FRP bars exhibit a linear elastic stress–strain relationship when pulled, very distinctly from the nonlinear behaviour of steel bars. The surface of FRP bars can be modified to increase bonding with concrete. Several methods can be used for this purpose, such as ribs, sand coatings, helical wrapping, or even braiding, as shown in Figure 3.
FRP bars made from thermosetting polymers cannot be reshaped after production. In contrast, those produced with thermoplastic resins can be reheated and reformed, providing greater flexibility for various design applications [36]. However, the tensile strength of bent FRP sections is 40–50% lower than that of straight sections [36]. Table 1 summarizes the key mechanical properties commonly provided by FRP manufacturers [36], [37]. These properties include yield strength for steel bars (f_y), tensile strength (f_u), rupture strain of FRP (ε_{fu}), elastic modulus (E), and yield strain (ε_y).

Table 1: The standard tensile properties for reinforcing bars of all materials according to ACI 440.1R (2006) and CAN/CSA S806-12 (2012) [36, 37].

Type	E(GPa)	f_u(GPa)	f_y(GPa)	ε_{fu}(%)	ε_y(%)
GFRP	35.0 – 51.0	0.483 – 0.69	---	1.2 – 3.1	---
AFRP	41.0 – 125.0	1.72 – 2.54	---	1.9 – 4.4	---
CFRP	120.0 – 580.0	0.6 – 3.69	---	0.5 – 1.7	---
BFRP	30.0 – 80.0	0.8 – 1.68	---	2.6 – 3.1	---
Steel	200	0.483 – 1.6	0.260 – 0.517	---	0.14 – 0.25

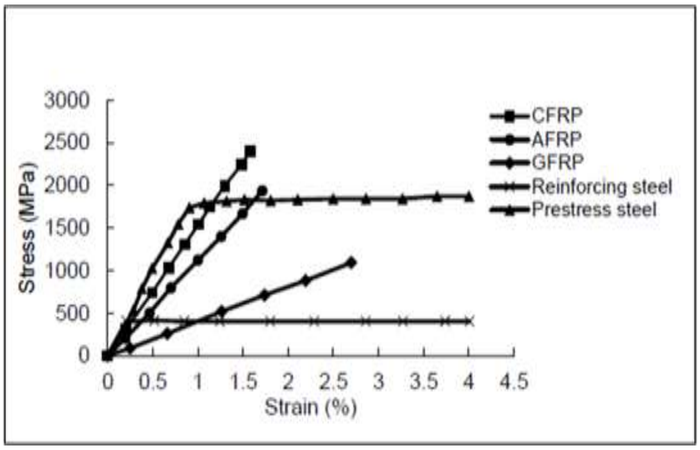

Fig. 1: Steel and FRP bar stress-strain correlations [38].

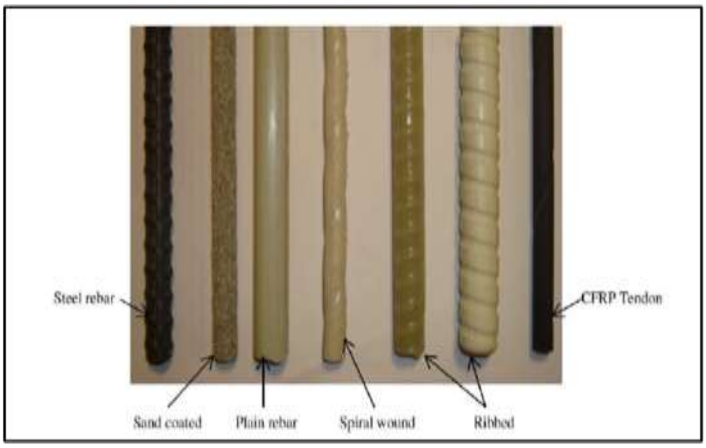

Fig. 2: Different types of FRP bars surface-treated [39].

3. Bond behaviour of FRP bars and modes of bond failure

The bond behavior between FRP bars and steel bars differs significantly due to variations in material properties and their interaction mechanisms with concrete. According to ACI 408R-03 [40], the primary mechanisms enabling load transfer between concrete and reinforcement are chemical adhesion, friction, and mechanical interlock, as illustrated in Figure 4.

In the case of steel bars, it is mainly the mechanical interlock that takes place and aids in stress transfer between concrete and reinforcement. This happens in FRP bars to a relatively lesser extent because of their surface texture. Steel bars have their surface designed to increase the mechanical interlock; most FRP bars are manufactured with an epoxy or fiber or sand coating on the surface, resulting in a texture that is not homogeneous, unlike that of steel bars.

FRP bars are made up of a non-homogeneous, anisotropic linearly elastic substance. The reason their anisotropic behaviour comes into place is the variation of the mechanical properties. In which case, longitudinal strength is mostly contributed by the fibres, then the transverse strength and shear resistance come from the resin matrix [41]. This non-uniform mix reduces the efficiency of mechanical interlock; hence, the bond performance is lower than that of steel reinforcement.

Confinement is essential for controlling radial and tangential stresses along the rebar, keeping them within the concrete's capacity and thereby preventing bond failure. In simply supported deep beams, anchorage methods differ due to the inability to bend FRP bars. Consequently, most studies have concentrated on increasing the embedment length of FRP bars beyond the load application point to achieve adequate anchorage. Extensive research has been conducted to explore this aspect [42-45].

Primary bond failure modes between the reinforcement and surrounding concrete are identified as splitting failure and pullout failure. These are mainly stress mechanisms at the concrete-rebar interface. Splitting does not occur within the bar itself appears. It is mainly when the distance or layer of concrete is lacking, as in Fig. 5. When loaded, the bars put pressure on the inside of the concrete; it cracks where the cover and/or spiral support cannot hold back against this pressure. The cracks begin at the center of the bar where contact exists and move to the outer edge, hence breaking the cover outside, leading to bond failure. Pullout failure depicted in Fig. 6 transpires if there exists adequacy in concrete cover, bar spacing, and transverse reinforcement to resist splitting failure. In such conditions of bond failure, it takes place by the shear of the concrete keys formed around the bar ribs; therefore, the rebar slips out of the concrete without splitting the cover. For steel reinforcement, if the anchorage is good, the reinforcement may get to its yield strength before the bond fails. But, with FRP reinforcement the failure mechanism is different due to the unique properties of FRP bars. Even if FRP bars have a better tensile strength as compared to steel bars, the bond strength with concrete is normally lower than their tensile strength. Hence, bond failure in FRP-reinforced sections normally happens before the bars get to their tensile capacity. This shows clearly how very essential proper anchorage design is to prevent premature bond failure.

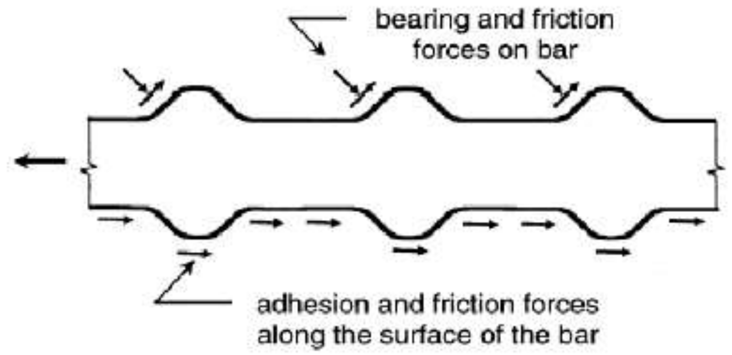

Fig. 3: Bond force transfer mechanisms [40].

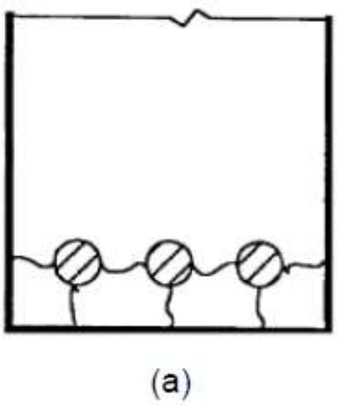

Fig. 4: splitting cracks between bars and concrete cover.

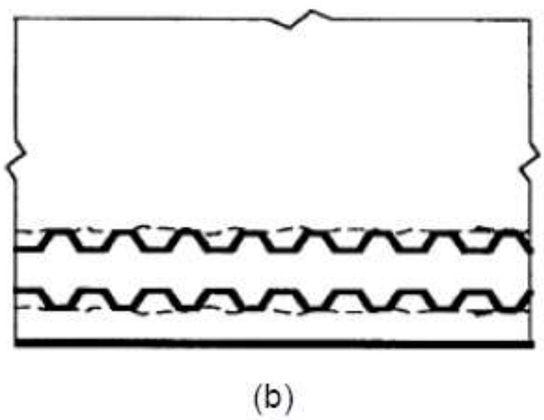

Fig. 6: pullout failure.

4. Flexural behaviour of FRP-reinforced concrete beams (FRP-RC)

The bending behaviour of FRP-RC beams differs from steel-reinforced beams because of inelastic characteristics presented by FRP bars. The latter presents a linear relationship between stress and strain until failure of the bar. This is where two types of failures can be registered, which is either concrete crushing (compression failure) or FRP failure (tension failure). It is preferable to fail to compress; good audible signals are visible before collapse. On the contrary, tension failure is sudden and devastating. It is highly undesirable [36]. Many tests and ideas were done to study how concrete cylinders with FRP sheets act [46–49].

Benmokrane and Masmoudi [47], in their test on beams reinforced with FRP under low stress, found that pattern width of fracture of GFRP-RC beams is similar to that of steel-RC beams. An increase in stress on the GFRP reinforced beam resulted in more wide cracks that could be seen across the depth of the beam, while in the steel beam, the cracks were much narrower and less frequent. Another observation made by Sam and Swamy [49] was that the FRP-RC beams can deflect a span/250 compared to steel-RC beams under the same load.

New work has looked into the best ways to build with FRP-RC. Some groups have made official rules for design codes that are special to concrete [36, 37, 50, 51]. The ratio of reinforcing material for FRP greatly affects the flexural behavior of FRP-RC beams. It was noted by Theriault and Benmokrane [52] under conventional structures of RC that increase in reinforcement ratio decreases the length and the spacing of flexural cracks. Similar findings for continuous modes were noted by Adam et al. [53] and Habeeb and Ashour [54] who found that the ultimate capacity was better with a higher percentage of reinforcement, while also leading to a reduced value of crack width and mid-span deflection. Following the rules of ACI 440.1R-06, in the paper by Kassem et al. [55], it was suggested that the reinforcement ratio should be adopted greater than 1.4 times the balanced reinforcement ratio so that failure may be ensured to be caused by the concrete and not by a sudden burst of reinforcement.

5. Conclusion

The study on the flexural behaviour of FRP-strengthened concrete beams confirms that FRP significantly enhances structural capacity and performance. Experimental results across all tested cases demonstrated notable improvements in load-carrying capacity, stiffness, and crack control compared to unstrengthened beams. The findings highlight that the effectiveness of FRP strengthening depends on bonding methods, FRP type, and layer configuration. Common failure modes, such as FRP debonding or rupture, underscore the importance of proper installation and anchorage systems. Overall, the results establish FRP as a viable and effective material for strengthening concrete structures, extending service life, and improving flexural performance. This study provides valuable insights for future research on retrofit design guidelines and application practices.

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